FIBRES & TEXTILES in Eastern Europe

sciendo

FIBRES & TEXTILES in Eastern Europe

Research Article • DOI: 10.2478/ftee-2024-0019 FTEE • 32(2) • 2024 • 57–63

Sustainability Approach of Recycled Denim Fabrics with a Life Cycle Assessment

Hakan Karagöl[1], Füsun Doba Kadem[2]*, Halil İbrahim Olucak[1], Mehmet Kertmen[1], Şehpal Özdemir[2]

[1] *İSKUR TEKSTİL A.Ş., Kahramanmaraş/ Turkey*
[2] *Cukurova University, Textile Engineering Department, Adana, Turkey*
* *Corresponding author. E-mail: efsun72@cu.edu.tr*

Abstract

In this study, denim fabrics were produced using weft yarns obtained from mechanically recycled fibers after consumer use, and the breaking strength, tearing strength, thermal resistance, water vapor permeability, air permeability, and fabric stiffness of these fabrics were determined according to the standards. A life cycle analysis of the recycled denim fabrics was made using the SimaPro software program, and the environmental effects of the production were also revealed. Within the scope of the study, it was observed that the structural properties of the fabrics produced and the composition of recycled cotton used affect the performance and comfort properties of the fabric. The effect of the cotton recycling rate on the recycled denim fabrics was evaluated by LCA (life cycle analysis). As a result of the LCA evaluation, with the use of cotton with a high percentage of recycling additives instead of the conventional cotton, as in the reference fabric, resource depletion (fossil fuels), global warming, depletion of the ozone layer, the toxic effect on human, freshwater and terrestrial life, the total water use, and other categories were observed to undergo a significant improvement.

Keywords

Denim, recycle fiber, recycle yarn, sustainability, life cycle assessment, cotton, pre-consumer, comfort.

1. Introduction

Denim is one of the most common fabrics worldwide. The volume of jeans produced by textile manufacturers and used by consumers is substantial. For this reason, environmental degradation associated with denim fabric production is extremely dangerous. Studies in the literature on recycling in the denim industry are increasing day by day. Denim textile wastes are generated during the production process in textile factories or after consumer consumption. It is defined as any clothing or household items made of textile material that the consumer no longer needs and decides to discard [1].

The use of recycled materials (fiber, yarn, and fabric) in the production of denim products has become even more critical to increase the recycling potential of cotton to meet the current and future market demands of the textile and ready-made clothing industry. The decision to use recycled materials in products occurs at the design and product development stage and continues throughout the production [2]. Recycling is the process of transforming waste materials into new materials and objects. The recyclability of a material depends on its ability to regain the properties it had in its original state. The main components of recycling are reduction, reuse, and recycling, and it has progressed to the stages of rebuy as the 4th component and recovery as the 5th in the textile industry. These recycling processes are generally divided into two methods: mechanical or chemical recycling of fibers [3]. The main difference between mechanical and chemical recycling is the eliminating or reducing of wet processing in the mechanical recycling system [2].

In general, the recycled textile material production cycle is shown in Figure 1 [4]. Mechanical recycling is the process of making textile waste reusable through physical processes. It consists of two main processes: separation of waste material and mechanical separation of the fabric. In mechanical recycling, recycled materials are classified accordingly depending on fiber type, color, quality, etc. This process includes the sorting, cleaning, and re-fibering of textile waste. This fiber can then be used in new textile products [5].

The textile denim industry in our country is turning to sustainable and environmentally friendly production methods [6]. At this point, sustainable denim must include a life cycle at all stages to minimize the environmental harm. For this reason, designing life cycle analysis is more important than product design [7]. Life cycle assessment enables the calculation of wastes and emissions resulting from all inputs, such as energy, raw materials, chemicals, and water used to produce or deliver a product, process, or service. Accordingly, it is a scientific analysis method that creates opportunities for making necessary improvements and reducing natural resource consumption [8]. The life cycle of denim fabrics begins with the production of raw materials such as fiber and chemicals. In addition to raw materials, energy and water are also used in fabric production, which causes air and water emissions and production waste [2].

Alp et al. conducted a comparative study of yarns produced using the rotor spinning method with recycled cotton (r-COT) and a cotton (COT) blend used in different proportions. They examined the results of the properties of these yarns (volume irregularity, Uster hairiness, defect index, breaking strength, and elongation at break). All analysis results of the fabrics produced were examined, and it was

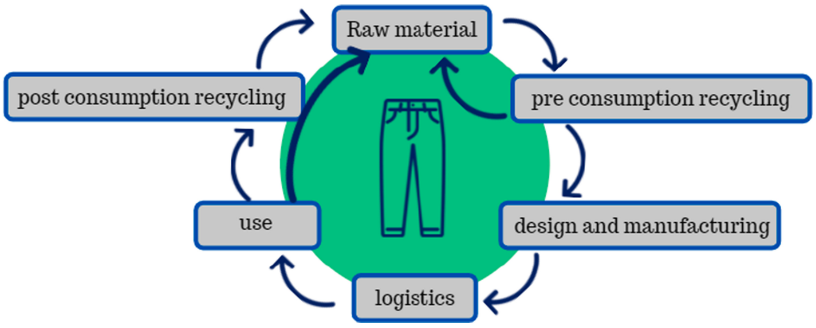

Fig. 1. Production cycle including recycled textile material [4]

determined that as the recycled cotton composition increased, the weft strength, warp and weft tear strength, relative water vapor permeability, thermal conductivity, and thermal absorption values decreased and thickness values increased [9].

In the study by Okandan et al. (2023), open-ended rotor (OE) yarns were spun from a 50/50 blend of recycled cotton (r-CO) and virgin cotton (C) fibers from pre-consumer cotton products. The effect of production parameters (rotor type, core type, and torque type) on yarn properties was investigated. It was concluded that 50/50 r-CO/C open-end rotor yarn samples produced with the narrowest rotor type, spiral, and green torque type caused lower hairiness and IPI, and higher elongation [10].

Alexander, E. S. (2023) measured the effect of using recycled cotton in denim fabrics on fabric strength quality and performance characteristics compared to minimum standards. As a result of the performance tests performed on denim fabrics, it was measured that the warp tear strength decreased; but all fabrics exceeded the minimum performance standards [11].

İvedi et al. (2019) ensured the collection of post-user denim waste. The cotton fiber was recycled and blended with virgin polyester for good tensile strength. Indigo-dyed fabric denim fabric was produced for pockets and compared with traditional pocket fabric. No significant effect on strength properties was observed between recycled yarn and conventional yarn. These results showed that fabric-containing materials could be used as pocket-recycled fabric for denim fabrics [12].

In Doba Kadem and Özdemir's study, some comfort features of denim fabric produced using recycled fibers after consumer use (PC denim) and original denim fabric of the same construction (REF denim) were determined and compared. In the study, air permeability, stiffness, and determination of dimensional change during the washing and drying of post-consumer denim fabrics were determined according to the standards. According to the results, this recycling process can be used effectively in denim production [13].

In the study by Erayman Yüksel and Korkmaz, LCA determination was made for recycled cotton products for sustainable textile designs. It was shown that the use of cotton has a lower environmental impact than that of recycled BCI cotton in all environmental impact categories [7].

In another experimental study, the life cycle analysis (LCA) of finished fabrics produced as denim and sportswear products of soy protein fiber, an innovative natural fiber, was performed. In the study, eight different blends consisting of cotton, soybean fiber and cotton/soybean blend yarns were used in the weft of woven fabrics selected from the denim and sportswear product group. It was observed that soy fiber content does not adversely affect the fastness and performance of woven fabrics. All fabric samples in the study underwent life cycle analysis (LCA) separately for denim and sportswear lines. The best result was in the life cycle analysis study of soybean fiber; it was obtained in fabrics using 90% cotton - 10% soy fiber in the weft for denim fabric and 50% cotton - 50% soy fiber yarn in sportswear fabric production [14].

In another paper, within the framework of increasing the contributions to sustainable development goals and reducing the water footprint, the sustainable production potential of a factory producing denim fabrics was studied in association with the sustainable development goals. As a result of the evaluations, it emerged as a more dominant view that the factory's contribution to sustainable development goals should be evaluated according to the total production capacity. The sustainability evaluation made according to the total production capacity determined that the factory contributed approximately 12% to Sustainable Development Goal 12 in the period examined, according to both the life cycle assessment and material input per service methods. Although there is inconsistency in the life cycle assessment and material input per service method results, it was predicted that there are economic and environmental gain potentials related to Sustainable Development Goals 13, 14, and 15, and the sustainable production potential of the factory can be increased [15].

With another study, the tensile strength, tear strength and softness values of re-cyled denim produced by partial recycling of cotton waste and denim fabrics produced from 100% cotton in a denim enterprise that had had a significant share in the sector in recent years were determined according to standards and the results were interpreted. As a result, it was determined that the recycling process in the denim production process can be used beneficially in denim production [16].

Another study investigated the contribution of the use of organic cotton fiber to the environmental impact of denim fabric, instead of conventional cotton fiber. The CML-IA method was applied to investigate the result of substituting organic cotton instead of conventional cotton. As life cycle

Samples	Warp Yarn	Weft Yarn
Reference (R)	Ne 6.5/1 Open End 30% Recycle / 70% Cotton	Ne 13/1 90% Cotton+7.5% Polyester+2.5% Elastane Modified Ring
D1		Ne 13/1 50% Cotton+40% Recycle Cotton+7.5% Recycle Polyester+2.5% Elastane Modified Ring
D2		Ne 13/1 40% Cotton+50% Recycle Cotton+7.5% Recycle Polyester+2.5% Elastane Modified Ring
D3		Ne 13/1 30% Cotton+60% Recycle Cotton+7.5% Recycle Polyester+2.5% Elastane Modified Ring
D4		Ne 13/1 20% Cotton+70% Recycle Cotton+7.5% Recycle Polyester+2.5% Elastane Modified Ring
D5		Ne 13/1 10% Cotton+80% Recycle Cotton+7.5% Recycle Polyester+2.5% Elastane Modified Ring

Table 1. Properties of yarns

Samples	%Um	% CVm	Index	H	sh	Breaking force (gF)	Breaking elongation (%)	Rkm (kgf×Nm)	B-work (gF cm)
R	8.58	10.86	1.87	6.28	1.35	1019.84	8.08	17.27	2083.26
D1	6.75	8.52	1.49	6.86	1.63	814.68	11.98	16.56	2064.00
D2	8.12	10.28	1.80	7.39	1.75	746.88	11.30	15.18	1292.89
D3	8.79	11.19	1.95	7.52	1.91	745.33	11.68	15.15	1350.68
D4	10.61	13.78	2.41	8.14	2.06	652.90	9.57	13.27	1903.17
D5	10.84	13.56	2.37	8.58	2.22	646.03	9.06	13.13	1845.35

Table 2. Yarn properties

inventory, primary production data were used during denim production as well as secondary data from the Ecoinvent Database. LCA application from the cradle to the gate was implemented using Simapro 8.5.2 software. As a result of that LCA study, all environmental impacts of denim fabric decreased with the use of organic cotton. A significant reduction in fresh aquatic ecotoxicity by 96% was achieved compared to the use of conventional cotton. Moreover, in terrestrial ecotoxicity and photochemical oxidation potentials, quite remarkable improvements were made, 90% and 57%, respectively [17].

In this study, denim fabrics were produced using weft yarns obtained from mechanically recycled fibers after consumer use, and the breaking strength, tearing strength, thermal resistance, water vapor permeability, air permeability, and fabric stiffness of those fabrics were determined according to the standards. The results obtained indicate that this recycling process can be used effectively in denim production. A life cycle analysis of the recycled denim fabrics was made using the SimaPro software program, and the environmental effects of the production were also revealed.

2. Material and Methods

Weft yarns with an ayarn count of Ne 13/1 were used in the study. Six different raw materials were used to produce different denim woven fabrics, one of which is reference denim with a 3/1 Z twill weave structure. The warp thread of all fabrics was Ne 6,5/1 Open End 30% Recycled / 70% Cotton.

Warp and weft properties are given in Table 1 [18]. In this study, various recycled fibers (cotton, polyester, elastane) and different recycled cotton compositions (80-70-60-50-40%) were used. Yarns were produced with a new modified ring spinning method and the conventional ring spinning method, and denim fabrics were obtained from those yarns. The yarns used in the study are post-consumer recycled yarns.

Unevenness test results of the recycled blended yarns used in the study are shown in Table 2 [18], and the strength test results are given in Table 3.

When the unevenness measurements were examined, it was determined that the unevenness was higher with an increase in the rate of recycled cotton. The hairiness of yarns containing recycled cotton is much higher than for yarns produced from conventional cotton. The lowest hairiness value belongs to the reference yarns, as expected. In yarns using recycled cotton, the excess of short and unproductive fibers attached to the yarn increases the hairiness value of the yarns. If the table is evaluated in general, it can be said that the yarn unevenness and some yarn properties (thin places, thick places, neps) increase with an increase in the recycling rate.

As can be seen in Table 2, it was observed that after the reference yarn, the sample with the highest strength values and the lowest recycle rate was number D2. It can be said that the strength (Rkm) decreases as the sample goes from D2 to D6, and in this case, the specific strength (Rkm) value decreases as the recycle rate increases in the mixture. As the recycling rate increased, the yarn strength values decreased up to 36.65% compared to the reference fabric. Tests and standards applied to denim fabrics with 5 different recycling rates are given in Table 3.

Test No	Test name	Test Standard
1	Standard Test Methods for Mass Per Unit Area (Weight) of Fabric	ASTM D3776: 2020
2	Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test)	ASTM D5034: 2021
3	Standard Test Method for Tearing Strength of Fabrics by Falling-Pendulum (Elmendorf-Type) Apparatus	ASTM D1424: 2021
4	Standard Test Methods for Stretch Properties of Fabrics Woven from Stretch Yarns	ASTM D3107: 2019
5	Textiles - Physiological effects - Measurement of Thermal and Water-Vapor Resistance under Steady-State Conditions (Sweating Guarded-Hotplate Test)	TS EN ISO 11092: 2014
6	Textiles the Assessment of Drape of Fabrics.	TS 9693: 1991

Table 3. Tests applied to denim fabrics

Sample Number	Unit weight (gr/m²)		Weft per inch		Warp per inch		Thickness (mm)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
R	377	2	46	0	67	0.816497	0.754	0.005
D1	385	1	46	0	74	1.632993	0.768	0.007
D2	388	1,73	47	1.632993	69	0	0.764	0.005
D3	378	3	46	0.816497	68	0	0.752	0.004
D4	379	2,64	45	1.414214	65	0.816497	0.760	0.006
D5	382	3,46	47	1.632993	71	0.816497	0.782	0.007

Table 4. Physical properties of fabrics

Sample Number	Tensile strength (Kgf) (weft direction)		Tensile strength (Kgf) (warp direction)		Tear strength (gf) (weft direction)		Tear strength (gf) (warp direction)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
R	46	2.44	92	2.54	4957	162.39	6300	148.76
D1	43	3.39	90	2.54	4708	34.28	6083	135.79
D2	41	2.73	88	2.12	4657	80.76	5914	68.84
D3	39	2.64	88	2.34	4201	61.05	5817	123.93
D4	38	2.91	85	5.19	3945	66.64	5776	134.53
D5	36	3.39	87	4.74	3613	104.82	5903	120.89

Table 5. Tensile and tear strength results of denim fabrics

3. Results and Discussion

3.1. Selected Performance Properties of Denim Fabrics

Recycled denim fabrics were tested according to related standards, and their breaking strength, tearing strength, thermal resistance, water vapor permeability, air permeability, and fabric stiffness were determined.

The yarns obtained in the study were used as weft yarn. Warp yarn and density were kept constant in all fabric samples produced. Therefore, no significant difference was observed between the breaking strengths of the fabrics obtained in the warp direction.

When the weft tensile strength data were examined in general, there were significant differences between denim fabrics in the tensile strength in the weft direction (Table 5).

There is approximately a 22% difference in strength between the reference denim and the denim fabric with the highest recycling rate (R and D5 fabrics).

When the tear strength values of denim fabrics produced using recycled yarn were examined, it was observed that the weft tear strength decreased significantly with an increase in the recycling rate (from the R sample to the D5 sample). The strength loss difference between the reference fabric and the fabric at the highest recycling rate (R and D5 fabrics) is around 27%.

When the elasticity values of the denim fabrics produced were examined, it was observed that the elasticity decreased by 14% as one went from the R sample to the D5 sample (Table 6). It can be said that the reason for this is the weakness and complex structure of the fiber-fiber adhesion of the recycled cotton yarn, which is included in the yarns used in the weft. Therefore, as the recycling rate in the fabrics increases, the recovery ability decreases.

When the air permeability results were evaluated, it was seen that the use of recycling reduced the air permeability, except for some exceptional results. When the results are evaluated attentively, an increase in density can be seen in Table 4, which also affects the fabric porosity; hence, air permeability is related to

Sample number	Elasticity (%)		Air permeability (mm/s)		Stiffness (Kgf)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
R	42	1.58	56.491	1.497	0.784	0.106
D1	39	2.23	53.887	3.045	0.802	0.080
D2	38	2.54	52.525	1.852	0.795	0.027
D3	38	2.34	57.142	1.654	0.718	0.017
D4	37	2.12	60.118	2.705	0.790	0.027
D5	36	1.87	51.207	2.104	0.713	0.101

Table 6. Selected performance properties of denim fabrics

Sample number	Relative water vapor permeability (%)		Water vapor permeability (WVPR)		Thermal resistance (m^2K/W)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
R	52.42	0.94	4.71	0.45	0.003839	0.000134
D1	49.32	0.66	5.06	0.18	0.004068	0.000278
D2	48.18	1.28	5.46	0.24	0.004384	0.000116
D3	46.53	0.99	5.80	0.26	0.004553	0.001127
D4	46.46	0.67	5.50	0.20	0.004900	0.000898
D5	46.96	1.46	5.62	0.26	0.004944	0.000097

Table 7. Selected thermal comfort properties of denim fabrics

this situation. Likewise, the increase in weight is directly related to the softness of the fabric.

Some thermal comfort features were examined, the results of which are given in Table 7.

To investigate the thermal comfort properties of denim fabrics, water vapor permeability and thermal resistance tests were applied. Test results determined that different yarn types with the exact yarn count had a significant effect on the relative water vapor permeability values of the fabrics.

As the percentage of recycled cotton used in denim fabrics increases, the relative water vapor permeability (%) decreases. According to the measurement results, the highest relative water vapor permeability belongs to the denim fabrics woven with reference R yarns, in which 100% conventional cotton is used and no recycled cotton . There are more short fibers in yarns produced with post-consumer wastes. These short fibers form structures that prevent the advancement of water vapor with pubescence. This causes a decrease in the passage of water vapor.

When the thermal resistance values were examined, it was determined that the change in yarn type affected the thermal resistance values of the fabrics. As the composition of recycled cotton used in denim fabrics increased, the thermal resistance (m^2K/W) values increased. It is thought that this situation is due to the increase in the amount of compressed stagnant air with the rise in hairiness. According to the measurement results, the lowest thermal resistance value belongs to denim fabrics woven with reference R yarns, in which 100% cotton is used and no recycled cotton. Yarns produced with post-consumer wastes have more short fibers and a complex structure. As a result of the fabrics having a hairier surface, the thermal resistance was high. It is frequently stated in the literature that thermal resistance values increase when yarn hairiness (h) values increase, which is an expected result [18].

3.2. LCA Analyses of Denim Fabrics

All denim fabrics used in this study were produced under the same process conditions. A standard finishing process is applied to all denim fabrics. The starch size was used for sizing. The warp threads of all fabrics were indigo dyed, and commonly used indigo dyeing process conditions and recipes were applied. Burning, washing, finishing (fixing), and sanforizing processes are the finishing processes that denim fabrics undergo, respectively. Percentage improvement results of LCA data on other fabrics compared to the reference fabric were calculated. There is only a difference between the fabrics' recycling rates. Within the scope of the study, the effect of using recycled raw materials was evaluated with LCA (life cycle analysis) (Table 8) [18]. Simapro software is used when performing LCA to determine, report and control the environmental impacts of a product or service at each stage of its life cycle, from raw materials to the disposal of waste generated as a result of production. All production inventories were collected in order to enter data in the life cycle analysis. As a result of inventory analysis, a list was categorized based on environment (air, water, soil) or process emerges. Accordingly, the environmental impacts calculated in the life cycle assessment were determined and interpreted for the reference denim and recycled cotton-added denim. Life cycle analysis (LCA) of the denim fabrics obtained was made with SimaPro software (2018, vers. 8.5.2.2.), and as a result of the LCA evaluation, the effect of the use of cotton with a high percentage of recycling additives instead of the original cotton, as in the reference fabric, on resource depletion (fossil fuels), global warming, depletion of the ozone layer, the toxic effect on human, freshwater, and terrestrial life, total water use and other categories was revealed (Figure 2).

According to this, with D5 (10% Cotton + 80% Recycled Cotton + 7.5%) Recycled Polyester + 2.5% Elastane) the following results were obtained: global warming 13.6%, ozone depletion 9.66%, toxic effect on freshwater life 21.93%, total water use 18.14%, and toxic effect on human life 15.65%.

% improvement	Abiotic depletion	Abiotic depletion (fossil fuels)	Global warming	Ozone layer depletion	Human toxicity	Toxic effect on freshwater
R						
D1	9.75	7.28	7.16	4.82	8.09	10.76
D2	12.33	8.90	8.97	6.18	10.21	13.89
D3	14.36	10.17	10.38	7.24	11.87	16.35
D4	16.75	11.67	12.06	8.50	13.84	19.25
D5	**18.96**	**13.05**	**13.60**	**9.66**	**15.65**	**21.93**
% improvement	**Marine aquatic-eco toxicity**	**Terrestrial eco-toxicity**	**Photochemical oxidation**	**Acidification**	**Eutrophication**	**Total water use**
R						
D1	6.72	11.11	7.52	8.35	8.48	8.90
D2	8.44	14.35	9.43	10.60	10.85	11.48
D3	9.78	16.90	10.93	12.37	12.72	13.52
D4	11.37	19.90	12.71	14.47	14.93	15.92
D5	**12.84**	**22.68**	**14.34**	**16.40**	**16.97**	**18.14**

Table 8. Percentage improvement results of life cycle analysis

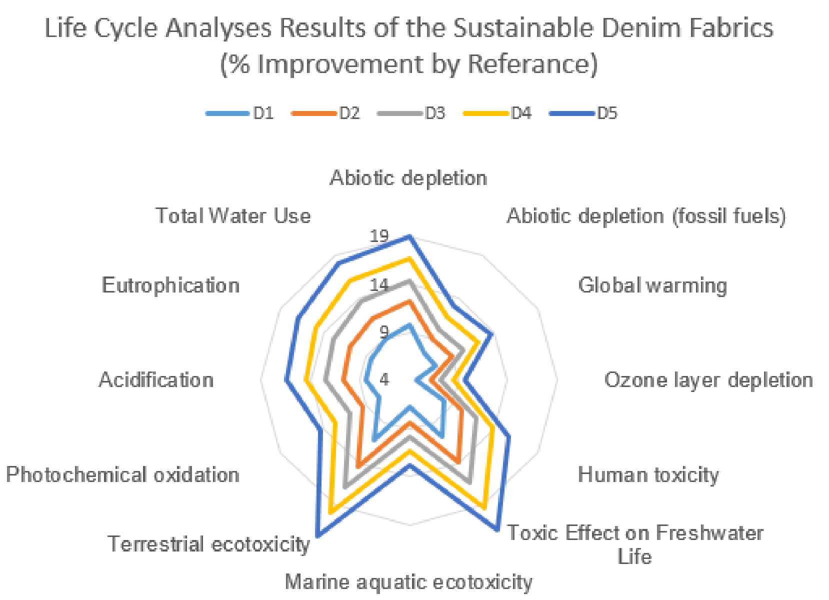

Fig. 2. Graphic representation of life cycle analysis improvement

4. Conclusion

Within the scope of this study, denim fabrics with a high recycling rate were produced using yarns produced from the recycling of cotton, one of the most important raw material sources for the textile industry, and the performance properties and thermal comfort properties of these fabrics were examined. For denim fabrics, yarns were obtained using polyester and elastane, and recycled cotton was used at various rates as weft yarn. Denim fabrics with a 3/1 Z twill weave structure were produced using cotton (70% conventional cotton, 30% recycled cotton) yarn as the warp yarn. Tests of the breaking strength, tear strength, elasticity, thermal resistance, water vapor permeability, stiffness, and air permeability of the denim fabrics were made, and the change in the recycling rate was evaluated in terms of fabric usage performance. Within the scope of the study, it was observed that the structural properties of the fabrics produced and the composition of recycled cotton used affect the performance and comfort properties of the fabric. The effect of the cotton recycling rate on recycled denim fabrics was evaluated by LCA (life cycle analysis).

As a result of the LCA evaluation, with the use of cotton with a high percentage of recycling additives instead of the conventional cotton, as in the reference fabric, resource depletion (fossil fuels), global warming, depletion of the ozone layer, the toxic effect on human, freshwater, and terrestrial life, total water use, and other categories were observed to undergo a significant improvement.

In addition, since the process flow is the same for all samples during production, the rate of improvement in environmental impacts only comes from the effect of recycling.

Essentially, in this study, fiber was obtained by recycling from fiber and yarn wastes generated during the yarn production phase in a denim enterprise, where pre-consumer yarn was produced by mixing recycled fibers at different rates, and denim fabrics were obtained at different recycling rates. All production was made in the same denim facility.

With this study, it was aimed to reveal the importance of more environmentally friendly denim fabric production by increasing the recycled fiber ratio, and the impact of denim fabrics on the life cycle in terms of sustainability was evaluated with LCA. It was also stated that consumers can choose sustainable denim and that these fabrics are suitable for use in terms of performance properties.

Acknowledgment

As the authors, we would like to thank İSKUR TEKSTİL A.Ş. (Kahramanmaraş/TURKEY) for their support to the study and Çukurova University Textile Engineering Department for the laboratory support provided in the conduct of the tests.

Conflict of Interest

The Authors declare there is no conflict of interest.

References

1. Kertmen, M., Doba Kadem, F. and Karagöl, H., A Study On Classified Quality Characteristics of Post-Consumer Recycled Cotton Knitted Fabrics, XVth International İzmir Textile and Apparel Symposium October 26-27, 2021, Turkey, pp. 216-223.
2. Uncu Akı, S., Candan, C., Nergis, B., Önder, N. S. Understanding denim recycling: A quantitative study with lifecycle assessment methodology. In Waste in Textile and Leather Sectors. IntechOpen, 2020.
3. Payne, A. Open- and closed-loop recycling of textile and apparel products. Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing, pp:103–123, 2015. doi:10.1016/b978-0-08-100169- 1.00006-x
4. Contin, B., Kohan, L., Duarte, L. O., Fernandes, P. R. B., Ruchel-Soares, R., Siqueira, M. U., & Baruque-Ramos, J. Brazilian Cotton Jeans Recycling: Characterization of Shredded Pre-Consumer Waste. Materials Circular Economy, 2022; 4(1), 19.
5. Neuß J, Schlich M. Best Before: A selective service life analysis of denim fabrics with a focus on washing and drying degradation to optimize their recycling efficiency [thesis]. The Swedish School of Textiles: University of Boras; 2019.
6. Amutha, K., Environmental impacts of denim, Sustainability in Denim, 2017; pp:27–48. doi:10.1016/b978-0-08-102043-2.00002-2
7. Erayman Yüksel, Y., Korkmaz, Y. Eco-Friendly Denim Fabric Design and Life Cycle Analysis, Kahramanmaras Sutcu Imam University Journal of Engineering Sciences, 26(1), 117-125, 2023.
8. Teke Ş., Tekstilde Çevre "Tekstil Terbiye Sektöründe Temiz Üretim İçin Örnek Modellerin Oluşturulması" Projesi Teknolojik Değerlendirme Raporu, ISBN 978-605-85527-3-9, BUTEKOM Bursa Tekstil & Konfeksiyon Ar-Ge Merkezi, Bursa
9. Alp G., Yıldırım, N., Kertmen, M., & Türksoy, H. Investigation of Performance Properties of Denim Fabrics Produced from Recycled Cotton Blended Yarns, DEUFMD, 25(74), 275-285, 2023.
10. Okandan, H., Yıldırım, N., Kertmen, M., & Türksoy, H., The Effects of Oe-Rotor Spinning Parameters On Yarn Properties Produced from Recycled/Virgin Cotton Fibers Blend. Uluslararası Bilim Teknoloji ve Tasarım Dergisi, 2023; 4(1), 1-15.
11. Alexander, E. S., Evaluation of the Effect of Using Recycled Cotton Fibers on the Fiber Quality, and Performance Properties of Cotton Denim Fabrics, 2023.
12. Ivedi, İ., Güneşoğlu, B., Yaffe, H., & Topbasan, S., Closing The Loop: Step One Pre-Consumer Denim Fabric Wastage Recycling Process, In Proceedings of the 19th World Textile Conference-Autex 2019.
13. Doba Kadem F., Özdemir Ş., A Study on Selected Comfort Properties of Post-Consumer Recycled Denim Fabrics Çukurova University Journal of the Faculty of Engineering and Architecture, 2000; 35(2), pp. 379-388
14. Sabır, E. C., Sırlıbaş, S., Dönmez Uzun, İ., Civan Yiğit, D. Yenilikçi Soya Lifi İçeren Mamul Denim ve Spor Giyim Kumaşların Yaşam Döngüsü Analizi (LCA). Çukurova Üniversitesi Mühendislik Fakültesi Dergisi, 38(4), 887-898, 2023. https://doi.org/10.21605/cukurovaumfd.1410190
15. Sarı, B., Zarifi, F., Alhasan, M., Güney, H., Türkeş, S., Sırlıbaş, S., Civan Yiğit, D., Kılınççeker, G., Şahin, B., Keskinkan, O. Determining the Contributions in a Denim Fabric Production for Sustainable Development Goals: Life Cycle Assessment and Material Input Approaches. Sustainability 2023, 15, 5315. https://doi.org/10.3390/su15065315
16. Tölek, Ş., Doba Kadem, F. Denim kumaşların mukavemet özellikleri üzerine bir çalışma. 1st International Mediterranean Science and Engineering Congress (IMSEC 2016), October 26-28, 2016, Adana/Turkey.
17. Fidan, F. S., E. K. Aydoğan, and N. Uzal. A Comparative Life Cycle Assessment of Conventional and Organic Cotton in Denim Fabric. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://uest.ntua.gr/thessaloniki2021/pdfs/THESSALONIKI_2021_Fidan_et_al.pdf
18. Karagöl H., Investigation of the effect of improving recycle cotton ratios on fabric comfort and performance properties in denim woven fabrics, MSc thesis. Adana: Çukurova University Institute of natural and applied sciences, 2023.